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Enhancing green ports in Dar es Salaam Port: facility optimization for emission reduction through Mamdani and Sugeno Fuzzy inference systems

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This study rigorously assesses emissions from diverse equipment at Dar es Salaam Port, analyzing CO, NOx, SO2, PM10, and POC emissions across various areas. Detailed data collection includes machine specifications, and calculated emission factors that facilitate precise analysis. The research design includes both evaluation of emissions and a strategic phase for optimizing equipment towards reduction. This study employs Mamdani and Sugeno Fuzzy Inference Systems (FIS) to comprehensively analyze emissions from diverse equipment within Dar es Salaam Port. The FIS enhances precision in emission reduction target-setting by considering the intricate parameters, unique to each equipment type. In 2022, the cumulative emissions of CO, NOx, SO2, PM10, and POC amounted to 185,163, 92,908.4, 40,842.4, 8,067.53, and 9,178.614 pounds, respectively, forming a basis for evaluating sustainability initiatives. Strategic interventions are delineated for each equipment type, from advanced technologies for Rubber-Tired Gantry Cranes (RTG) and systematic replacements for Forklifts. Overarching initiatives include regulatory frameworks, alternative fuels, and technology transitions. The FIS models specify emission reduction targets, such as Mamdani proposing a reduction of 12,504.51 pounds of CO from Berthing Tugs, and Sugeno suggesting 3,751.353 pounds. These nuanced recommendations integrate into a strategic roadmap, guiding Dar es Salaam Port towards a sustainable future.

KEYWORDS

Mamdani FIS, Sugeno FIS, emissions reduction, sustainable port, renewable energy adoption, Dar Es Salaam Port

1 Introduction

Green ports represent an innovative concept in the maritime sector, aiming to revolutionize port operations by prioritizing sustainability and environmental responsibility (Haezendonck, 2021). As the world increasingly acknowledges the urgent need to combat climate change and protect natural resources, green ports have emerged as crucial players in promoting sustainable practices within the shipping and logistics industry (Di Vaio and Varriale, 2018). Unlike traditional ports that solely focus on commercial aspects, green ports take a holistic approach, integrating eco-friendly principles into their core operations.

FIGURE 1
Proposed model flow chart for examination of total emission at dar Es salaam port.

The significance of green ports lies in their potential to foster a harmonious coexistence between port activities and the environment (Pop et al., 2023). By embracing innovative technologies and sustainable infrastructure, these ports aim to minimize their ecological footprint and reduce adverse impacts on surrounding ecosystems (McKinnon et al., 2024). Emphasizing energy efficiency, waste management, emissions reduction, and the preservation of biodiversity, green ports contribute significantly to global efforts in achieving climate goals and ensuring the wellbeing of future generations.

Moreover, the development of green ports aligns with international agreements and initiatives like the United Nations Sustainable Development Goals (SDGs) and the International Maritime Organization's (IMO) climate strategies. By actively pursuing sustainable practices, green ports position themselves as leaders in the quest for a greener and more resilient maritime sector. As the world's economies become increasingly interconnected, green ports also serve as beacons of change, inspiring other ports and stakeholders to embrace sustainable principles and collectively work towards a more environmentally conscious and sustainable future for the entire industry (The United Nations Conference on Trade and DevelopmentThe United Nations Food and Agriculture OrganizationThe United Nations Environment Programme, 2020), (Kikaki et al., 2024). In April 2018, the International Maritime Organization (IMO) adopted the 'Initial IMO Strategy on Reduction of GHG Emissions from Ships,' marking a milestone in its 2016 roadmap. (Doelle and Chircop, 2019) evaluates the strategy's alignment with the Paris Agreement's goals, and its strengths and weaknesses.

The utilization of Mamdani and Sugeno Fuzzy Inference Systems in this study addresses the intricacies of emissions reduction at Dar es Salaam Port. Fuzzy logic's flexibility and ability to handle imprecise conditions make Mamdani FIS apt for capturing qualitative aspects, while Sugeno FIS complements with its precision in quantitative analysis (Pop et al., 2023). Together, the integration of Mamdani and Sugeno FIS in this study provides a comprehensive and balanced methodology, capable of capturing both the qualitative and quantitative dimensions of the intricate sustainability challenges faced by Dar es Salaam Port. This hybrid approach enables us to navigate the complexities of emissions reduction with a higher degree of accuracy, offering valuable insights for informed decision-making and effective implementation of sustainability initiatives (Samavat et al., 2023).

Dar es Salaam Port, positioned along the Indian Ocean coastline in Tanzania, holds a pivotal role as a major maritime gateway within East Africa. Serving as the largest and busiest port in the country, it plays a crucial role in facilitating regional and international trade, connecting landlocked nations such as Zambia, Malawi, Burundi, Rwanda, and Uganda to global markets (Mwendapole and Jin, 2021). Despite its historical significance and economic contributions, Dar es Salaam Port faces environmental challenges, particularly related to emissions from its diverse facilities. This study aims to delve into the intricacies of the port's operations, analyzing the complex interplay between its dynamic activities and the resultant greenhouse gas emissions and to have green port as shown in Figure 1. By scrutinizing the unique attributes and challenges of Dar es Salaam Port, this research seeks to provide a nuanced understanding of the contextual factors influencing emissions within the port's facilities.

The motivation for this study stems from the critical need to address environmental sustainability in port operations, with a specific focus on Dar es Salaam Port in East Africa. By conducting a comprehensive analysis of emissions from each port facility, we aim to identify opportunities for optimizing these facilities. This research is driven by the urgency to minimize the environmental impact of port activities, enhance overall sustainability, and provide actionable insights for Dar es Salaam Port authorities to foster greener and more efficient port logistics.

While previous studies have explored various aspects of port sustainability, this research uniquely delves into the specific context of Dar es Salaam Port in East Africa, concentrating on a detailed analysis of emissions from each port facility. By narrowing the focus to this particular port, we aim to uncover site-specific challenges and opportunities for optimizing environmental performance. This study seeks to contribute distinctive insights into the sustainable development of Dar es Salaam Port, offering targeted recommendations for reducing \emissions and fostering a greener, more efficient maritime infrastructure.

The primary objective of this study is to comprehensively assess and analyze the emissions from various facilities within Dar es Salaam Port in East Africa. Through a detailed examination of each port facility's environmental footprint, the aim is to identify specific sources of emissions, quantify their impact, and offer strategic insights into optimizing these facilities for enhanced sustainability. This objective encompasses a nuanced understanding of the environmental challenges unique to Dar es Salaam Port, providing a foundation for the development of targeted and effective measures to mitigate emissions. Ultimately, the study seeks to contribute valuable knowledge that can guide the formulation of policies and practices for fostering a greener and more environmentally responsible port logistics system in the region.

2 Literature review

In this section, we delve into the literature surrounding Green Ports in East Africa, with a particular emphasis on optimizing facilities and operations to achieve sustainable port logistics.

The global maritime industry, driven by the ever-increasing demand for goods, is vital for international trade and economic growth (Cucco et al., 2024) (Musolino et al., 2022). Ports, acting as critical nodes in the global supply chain, are central to this industry's functioning. However, as trade volumes continue to surge, so do the environmental and sustainability challenges posed by port operations (Brunila et al., 2023). It has become evident that ports must evolve into "Green Ports" to reconcile economic development with environmental responsibility, particularly in regions like East Africa, where port logistics are instrumental for national and regional growth (The United Nations Conference on Trade and DevelopmentThe United Nations Food and Agriculture OrganizationThe United Nations Environment Programme, 2020). This chapter embarks on a comprehensive journey through the extensive literature surrounding Green Ports in East Africa, with a specific emphasis on optimizing facilities and operations to achieve sustainable port logistics.

2.1 Port sustainability and environmental concerns

Sustainability has emerged as a critical concern in port operations worldwide (Ogara et al., 2023). Ports, while essential for global trade, are known to have substantial environmental impacts. These include air and water pollution, habitat destruction, and emissions of greenhouse gases. Consequently, there is a growing consensus that ports must balance their role in facilitating trade with environmental responsibility. Research has increasingly focused on the burgeoning expansion of port cities in the Western Indian Ocean (WIO) and the Global South (GS) due to increased global trade. Recognizing the environmental and socio-economic impacts, a framework for assessing sustainability in these regions is proposed. The systematic literature review (SLR) reveals a bias towards Global North contexts, prompting the development of a unique framework grounded in the Drivers, Pressures, States, Impacts, and Responses (DPSIR) model, featuring 78 indicators. Validated through a Causal Network (CN) structure, it identifies 12 priority DPSIR CN, aligning with the UN Sustainable Development Goals for broader applicability. This framework facilitates robust sustainability reporting in emerging economy port cities, offering a comprehensive lens for evaluating land and sea interactions.

A noteworthy addition to this field is found in another paper (Di Vaio and Varriale, 2018). The literature underscores the increasing focus on environmental sustainability in seaports over the past 3 decades. Recognizing a gap in managerial practices, the study advocates for the adoption of the Balanced Scorecard and Tableau de Bord as managerial accounting tools to propel green port development. Additionally, the proposal emphasizes training as a crucial strategy to cultivate environmental awareness and behaviors among seaport personnel. The review underscores the urgent need for ongoing research and implementation of these measures within the seaport context.

Notably, (Lim et al., 2019), stands as a crucial contribution in this domain. The study adeptly synthesizes perspectives on sustainability performance in ports, emphasizing both operational and managerial facets. A distinctive feature is its holistic assessment of port sustainability, encompassing environmental, social, and economic dimensions. Unlike previous reviews, it adopts a unique approach, clustering sustainability indicators. Covering the span from 2005 to 2018, it highlights a significant surge in publications in 2017. The study not only offers valuable insights for decision-makers but also identifies prospective areas for future academic contributions in port sustainability. Subsequent sections delve into the definition and scope of port sustainability, a comprehensive literature review, the research methodology, a discussion on research questions, and conclusions, elucidating outlined contributions.

2.2 Global green port initiatives

Globally, Green Port initiatives have gained momentum in response to environmental concerns. These initiatives encompass a wide range of strategies aimed at reducing the environmental footprint of ports. Key areas of focus include improving energy efficiency, reducing emissions from port activities, adopting cleaner technologies, and enhancing waste management practices (Tawwk et al., 2024).

The "Green Port Policy: A Systematic Review of Factors Influencing Implementation Success" (GREEN PORT GUIDELINES, 2024) provides a systematic review of green port policies and their implementation worldwide. This review offers valuable insights into the factors influencing the success of green port initiatives. By synthesizing a wealth of literature, it presents a nuanced understanding of the challenges and facilitators of green port policy implementation, which is essential for guiding similar efforts in East African ports.

Furthermore, "Green Port Development: Examining the Gap between the Master Plan and Reality" (Fhoo and Fhoo, 2018) investigates the alignment between green port master plans and actual implementation. This research delves into the challenges faced by ports in translating sustainability goals into actionable strategies. Their findings shed light on the complexities of green port development and provide valuable lessons for ports in East Africa seeking to bridge the gap between planning and execution.

At the national level, (Chairman et al., 2024) the Government of India's Maritime India Vision (MIV) 2030, comprising over 150 actions, underscore the imperative for cultivating 'Safe, Sustainable, and Green Maritime Sectors.' India commits to reducing emissions and increasing renewable energy usage by 2030. Recognizing the pivotal role of ports in trade, there is a call for the adoption of green initiatives aligned with global commitments. The Ministry of Ports' 'Strategic Action Plan' lays out focus areas, stakeholder roles, and an implementation roadmap for realizing 'green ports,' with a focus on ensuring financial sustainability. This plan encompasses indicative projects and financing mechanisms, emphasizing the critical role of private sector investment in achieving MIV 2030 targets and fulfilling India's Nationally Determined Contributions (NDC).

As global environmental concerns escalate, the adoption of green port practices becomes increasingly crucial. This study (Yasin Kaya and Celik, 2017) initiates an exploration into green port policies, commencing with an examination of the USA, notably California's Long Beach Port, renowned for its groundbreaking greening initiatives. Subsequently, the research delves into the legal foundations of green port projects in Turkey, with a specific focus on Marport, acknowledged as the nation's inaugural green port. These case studies collectively contribute nuanced insights into the operational and legal dimensions of green port practices within diverse international contexts.

2.3 Green Port in Africa

In Africa, Green Port initiatives are gaining traction as ports seek to balance economic growth with environmental responsibility (Lawer et al., 2019). The study "Selective Adoption: How Port Authorities in Europe and West Africa Engage with the Globalizing "Green Port" Idea" explores how port authorities in Europe and West Africa selectively adopt green port tools and measures based on contextual factors. The research methodology involved 29 in-depth key informant interviews with port environmental officers, terminal operators, and maritime stakeholders from four ports in Europe and West Africa. The findings indicate that the selective adoption of green port tools and measures is influenced by environmental priorities, regulatory requirements, financial resources, and the immediate areas of competence of port authorities, which vary widely across regions and specific ports. The ports of Tema, Lagos, and Abidjan in West Africa have started implementing tools akin to the green port idea, understanding it as a catchphrase that promotes the idea of developing and operating ports with environmental and social considerations. The study also highlights the diverse green port practices implemented by these ports, including the establishment of infrastructure for waste reception and processing, in compliance with environmental regulations.

The study (Barnes-Dabban et al., 2017) examines how the Freeport of Monrovia in West and Central Africa adopted environmental considerations, labeling it "going green". Using Weick's sense-making and Weber and Glynn's institutional mechanisms, the research analyzes the process of assigning meaning and institutionalizing environmental reform. Empirical data from a 2013 project at the Freeport of Monrovia highlight the dynamic interplay of institutions and sense-making in the greening process. The findings provide insights into challenges faced by port employees and stakeholders in making sense of and institutionalizing environmental reforms within the port's specific institutional context.

In a pivotal study (ISEA, 2018), the transformation of Durban Port into a Smart City Eco-Port is explored. The proposal advocates for a 'Green Heart' anchored by a monumental sculpture at the harbor's entrance, symbolizing Durban's identity. Technological elements, including Apps and QR codes integrated with the KulturWalk, guide individuals into the harbor area. Emphasizing place-identity and placemaking, the theoretical framework envisions Durban's branding as the Green Heart City, with active resident participation in harbor custodianship (Ducruet et al., 2024). The proposed Green Heart Sculpture Sky Icon incorporates renewable elements, enhancing Durban Harbour's accessibility and Eco-Port identity. The literature suggests this transformation will boost Durban's recognition on tourist maps, highlighting its sustainability initiatives and overall city brand.

In a subsequent study (Elhamed and Mohamed, 2023), the investigation hones in on the implementation of the green port concept at Damietta Port in Egypt, a pivotal nexus for both local and international trade. The primary objective is to mitigate potential environmental threats, highlighting the significance of embracing sustainable practices for the wellbeing of current and future generations. The study underscores the pivotal role of green ports in not only lessening environmental impact but also bolstering societal, cultural, and economic values.

2.4 Mamdani and Sugeno Fuzzy inference systems (FIS)

In employing the Mamdani and Sugeno Fuzzy Inference Systems (FIS), this research strategically harnesses the power of fuzzy logic to address the complex and dynamic nature of emissions reduction in Dar es Salaam Port. Fuzzy logic provides a nuanced and flexible approach, particularly relevant in the context of sustainability, where imprecise and uncertain conditions often prevail.

The Mamdani FIS excels in handling linguistic variables and rule-based systems, making it well-suited for capturing the qualitative aspects of emissions and sustainability. By incorporating Mamdani FIS, we can effectively model the complex relationships between various factors influencing emissions, facilitating a more accurate representation of real-world scenarios (Rajesh Mavani et al., 2021).

On the other hand, the Sugeno FIS, with its mathematical structure and ability to generate precise outcomes, complements the Mamdani model. The Sugeno FIS is particularly advantageous when a more quantitative and deterministic analysis is required. Its suitability for data-driven decision-making enhances the robustness of our approach, ensuring a comprehensive evaluation of the emission reduction strategies (Benić et al., 2023).

The study (Pop et al., 2023) highlights the necessity of transitioning to Intelligent Transportation Systems (ITSs) for better urban traffic flow. It emphasizes the role of traffic modeling, particularly the car-following model, in understanding and controlling traffic behavior. The review addresses uncertainties in modeling and measurement errors, advocating for calibration processes. Specifically, it explores the effectiveness of Mamdani and Takagi–Sugeno fuzzy inference systems (FISs) in calibrating a continuous-time car-following model. The study concludes that while both fuzzy techniques are effective, Takagi–Sugeno FIS provides more accurate compensation values, crucial for developing autonomous driving solutions and ensuring collision avoidance in real-time.

Another study (Komsiyah and Desvania, 2021) addresses the diminishing effectiveness of traditional traffic light systems at intersections, emphasizing their unbalanced green light timing settings, which often neglect actual traffic conditions in each lane. The paper proposes a solution by formulating a dynamic green time setting system using the Mamdani type of Fuzzy Inference System. The author introduces a desktop-based application to simulate and analyze green light durations based on their proposed system. The resulting green light/green time output is compared to data from the transportation office of DKI Jakarta, revealing that the proposed method yields more dynamic and responsive outcomes, showcasing its potential for improving traffic flow at intersections.

Together, the integration of Mamdani and Sugeno FIS in this study provides a comprehensive and balanced methodology, capable of capturing both the qualitative and quantitative dimensions of the intricate sustainability challenges faced by Dar es Salaam Port. This hybrid approach enables us to navigate the complexities of emissions reduction with a higher degree of accuracy, offering valuable insights for informed decision-making and effective implementation of sustainability initiatives.

2.5 Optimization of facilities and operations

Efficient utilization of resources and optimization of port facilities and operations are central to achieving sustainability goals (Bjerkan and Seter, 2019). This paper focuses on the growing pressure for ports to address environmental impacts and promote sustainability. Examining 70 publications, the paper categorizes 26 tools and technologies across port management, power/fuels, sea, and land activities. However, it highlights a gap in empirical foundations for decision-making in ports, emphasizing the need for increased use of empirical data and understanding actors and processes in port decision-making for more effective sustainability strategies.

One of the foundational papers review focuses on shipping emission reduction, a critical concern in the transportation industry (Wang et al., 2023). Investigating the evolution of port emission reduction strategies, it emphasizes the impact of policies on research development. The review identifies a gap between energy and optimization operation measures for ship emissions in ports. The paper stresses the need for ports to understand their emission levels, establish inventories, and consider external factors before setting reduction targets. It underscores that port energy measures are crucial for achieving low and zero carbon goals. Looking ahead, the paper suggests addressing technical bottlenecks and integrating multiple measures for effective emission reduction. The overarching goal is to help ports, especially those with low abatement capacity, learn from experiences and challenges to contribute to environmental protection and global ecological development.

Additionally, (Parhamfar et al., 2023) Amid environmental concerns, the shipping industry faces pressure to adopt sustainable practices. This review explores green port initiatives, emphasizing the role of renewable energy technologies (RETs) like floating photovoltaic systems, offshore wind turbines, and ocean energy. The study assesses the potentials, challenges, and economic aspects of integrating RETs into ports. Notably, fuel cells are discussed as a flexible power source. Findings highlight that RETs can significantly contribute to making maritime operations more efficient and environmentally friendly.

Also (Geng et al., 2020) investigates optimal biodiesel processing plant locations, utilizing waste oil, through a novel weighting method integrating rough set theory and clustering algorithms. Empirical validation in China's Yangtze River Delta shows a substantial improvement in accuracy compared to conventional methods, with Root Mean Square Error (RMSE) and R-squared (R2) analyses confirming the efficacy of the proposed approach. Key factors, including waste oil supply (0.143), construction costs (0.343), biodiesel demand (0.143), and location convenience (0.371), are identified through this methodology. The study highlights the simplicity and efficiency of the proposed method, offering valuable insights for sustainable biofuel industry development.

2.6 Existing research on Green Port initiatives

In recent years, an array of research studies has explored green port initiatives and their impact on port sustainability and environmental conservation. These studies provide valuable insights into the strategies, challenges, and outcomes associated with the adoption of environmentally friendly practices in port operations.

One notable research endeavor is the work (Garg et al., 2023), amidst environmental challenges, are exploring sustainable solutions, including the establishment of green ports. This research identifies critical sustainability factors using the Fuzzy Analytic Hierarchy Process (FAHP) method. The top-ranked factors—Environment, Digitization, Automation, and Strategy—highlight key considerations. Sensitivity analysis confirms method robustness. Industry managers and policymakers are urged to adopt these factors for the establishment of sustainable green practices in Chinese ports.

Additionally in response to the global energy crisis, (Deng et al., 2022) examines the concept of green port development, acknowledging ports as significant energy consumers and pollution sources. The paper delves into the impact of government environmental regulations on green port construction, employing a tripartite evolutionary game model. Analyzing the strategic choices of the government, port enterprises, and transportation enterprises, the study suggests optimal strategies to promote green port construction, offering valuable theoretical guidance for stakeholders in the port industry.

In investigates how green roofs contribute to urban environmental improvements particularly in mitigating heat and managing stormwater, but faces specific challenges in Mediterranean regions (Hu et al., 2023). Researchers focus on identifying optimal plant species and construction methods for these unique climates. By examining factors like soil depth, organic content, and roof type, they aim to understand their impact on plant growth and overall green roof performance. Using data analysis techniques such as multiple regression and ANOVA, this study assesses the relationship between various parameters and plant growth on Mediterranean green roofs. Surprisingly, the results indicate that factors like soil depth and roof type do not directly correlate with plant growth. Instead, researchers emphasize the importance of considering plant communities and interspecies interactions, suggesting that these dynamics play a significant role in shaping overall vegetation performance (Aram et al., 2024). Looking ahead, the study suggests the need for further research to delve deeper into plant community dynamics and their influence on green roof effectiveness in Mediterranean climates. Additionally, exploring the impact of different roof types on plant communities is identified as a potential area for future investigation. Ultimately, understanding these complexities can inform more targeted strategies for maximizing the environmental benefits of green roofs in Mediterranean urban areas.

This literature (Hu et al., 2023) explores the forthcoming integration of the global shipping industry into the EU Emission Trading Scheme in 2024. Three allocation methods—historical, baseline, and mixed—are examined for their fairness in distributing emission quotas among typical shipping companies. Results indicate the mixed method as most efficient, projecting Pareto optimal allocation by 2024. Leading companies like Maersk are expected to hold substantial quotas, reflecting their prominence in EU routes. These findings offer insights for future emission management in the shipping sector, emphasizing equitable allocation and sustainability goals.

Furthermore, (Othman et al., 2022) evolving landscape of smart ports in response to the digital transformation and new business environment. Focusing on the development of a Sustainable Smart Port Index (SPI), the study conducts a systematic literature review, analyzing 48 articles to identify key pillars for smart port adaptation and their impact on sustainability. The paper emphasizes the need for an integrated index capturing various elements of smart ports, particularly in operations, environment, energy, safety, and security. While acknowledging existing SPI proposals, the study calls for further exploration, highlighting the importance of considering human resources in the context of smart ports for a more comprehensive and sustainable performance evaluation.

Moreover, the study (Nguyen et al., 2022) evaluates successful green port policies in developed countries, aiming to identify key features that enhance port efficiency and environmental friendliness. By drawing lessons from effective green port models, particularly in developed nations, the research highlights distinctive features applicable to developing countries like Vietnam. Notably, the implementation of these core features in international ports in Vietnam aligns with the national green port strategy, demonstrating efforts to establish legal and infrastructure frameworks for sustainable marine economic development by 2045.

The study (Tawwk et al., 2024) presents the Optimal Energy Hub approach for integrating renewable energy systems in smart green ports, focusing on Egypt's MIDTAP Company. By combining PV and wind energy with machine learning, it optimizes energy management, minimizing costs and emissions. Scenarios reveal insights into scaling up renewable energy, emphasizing careful planning within port constraints to achieve sustainable operations.

Lastly, (Dem et al., 2022) the research study explores the evolving concept of green ports, emphasizing their role as key hubs in maritime transportation and trade. With increasing global awareness, green ports aim to minimize environmental impact and enhance energy efficiency. The research employs a literature review method, focusing on two leading European ports to analyze energy efficiency practices. Port operations, equipment, and ships are scrutinized as energy-consuming elements. The qualitative analysis reveals that efforts towards energy efficiency in ports align with green port principles, marking a critical juncture in sustainable practices.

These studies collectively contribute to a comprehensive body of knowledge on green port initiatives, offering a multifaceted understanding of their implementation, impact, and potential challenges. Their findings serve as valuable resources for port authorities, policymakers, and researchers alike in their pursuit of sustainable port logistics in East Africa.

3 Methodology and data description

3.1 Data description

This research employs a comprehensive research design focused on evaluating the emissions from various equipment at the Dar es Salaam port. The study includes an in-depth analysis of CO (Carbon Monoxide), NOx (Nitrogen Oxides), SO2 (Sulfur Dioxide), PM10 (Particulate Matter with a diameter of 10 µm or less), and POC (Particulate Organic Carbon) emissions from each machine within different port departments, including the marine, container terminal, central workshop, and electricity workshop.

Data collection involves meticulous documentation of machine specifications, such as Equipment, Brand, Engine capacity, Sources of power, Consumption per hour (L), and Emission factors (per pounds/1,000 liters of fuel burned, per cubic meter of gas consumed, and per electricity unit consumed) as shown in Table 1. This detailed information, coupled with the calculated Emission factor per pounds/1,000 liters of fuel burned based on monthly machine operating hours, forms the foundation for precise calculations and analysis as shown in the following expressions from Equations 1–14.

Upon determining the total emissions produced by the port, the research design integrates a strategic component focusing on optimizing equipment to achieve emissions reduction. This dual-phase approach ensures a comprehensive understanding of the current emissions landscape and paves the way for the implementation of effective strategies to enhance environmental sustainability at Dar es Salaam Port. The structure of work flow of this paper are also shown in Error! Reference source not found.

The utilization of Mamdani and Sugeno fuzzy inference systems in this study effectively addresses the intricacies of emissions reduction at Dar es Salaam Port. Leveraging data from equipment at the port, including engine capacities, sources of power, fuel consumption per hour, and emission factors, Mamdani FIS captures qualitative aspects, while Sugeno FIS complements it with precision in quantitative analysis. This hybrid approach ensures a comprehensive methodology capable of addressing both the qualitative and quantitative dimensions of the sustainability challenges faced by the port.

For Mamdani fuzzy model, a fuzzy set A is defined with five memberships corresponding to pollutants: CO, NOx, SO2, PM10, and POC, denoted as a, b, c, d, and e, respectively. These membership functions characterize the degree of association of each pollutant with the fuzzy set, allowing for a nuanced representation of their impact on emission reduction targets. On the other hand, Sugeno fuzzy model operates similarly, employing fuzzy sets for CO, NOx, SO2, PM10, and POC, determined based on a different fuzzy logic approach. This enables the model to provide precise and specific control actions, making it suitable for situations where a clear, quantitative output is desired. As shown in expressions Equations 15–17.

The integration of Mamdani and Sugeno FIS enables the interpretation of complex and uncertain relationships between emission levels and reduction targets for each equipment type in Dar es Salaam Port. Results from comprehensive analysis, as depicted in Figure 2, showcase the annual total emissions for various equipment types, providing valuable insights for informed decision-making and effective implementation of emission reduction initiatives. This innovative approach not only enhances our understanding of emission reduction challenges at the port but also offers actionable recommendations for sustainable development and environmental stewardship.

The following expressions from 1 to 14 are derived for total emission calculation

$$E_{BRTj} = C \times \sum_{i=1}^{6}\left(Emission_{BRTij} \times Consumption_{BRTij} \times Hours_{BRTij}\right) \tag{1}$$

$$E_{POBj} = C \times \sum_{i=1}^{4}\left(Emission_{PLBij} \times Consumption_{PLBij} \times Hours_{PLBij}\right) \tag{2}$$

$$E_{MOBj} = C \times Emission_{MOBij} \times Consumption_{MOBij} \times Hours_{MOBij} \tag{3}$$

$$E_{POBj} = C \times \sum_{i=1}^{2}\left(Emission_{POBij} \times Consumption_{POBij} \times Hours_{POBij}\right) \tag{4}$$

$$E_{HOBj} = C \times Emission_{HOBij} \times Consumption_{HOBij} \times Hours_{HOBij} \tag{5}$$

$$E_{HOMCj} = C \times \sum_{i=1}^{11}\left(Emission_{HOMCij} \times Consumption_{HOMCij} \times Hours_{HOMCij}\right) \tag{6}$$

$$E_{RTGj} = C \times \sum_{i=1}^{2}\left(Emission_{RTGij} \times Consumption_{RTGij} \times Hours_{RTGij}\right) \tag{7}$$

$$E_{RSTj} = C \times \sum_{i=1}^{26}\left(Emission_{RSTij} \times Consumption_{RSTij} \times Hours_{RSTij}\right) \tag{8}$$

$$E_{TRCj} = C \times \sum_{i=1}^{48}\left(Emission_{TRCij} \times Consumption_{TRCij} \times Hours_{TRCij}\right) \tag{9}$$

$$E_{MOCj} = C \times \sum_{i=1}^{9}\left(Emission_{MOCij} \times Consumption_{MOCij} \times Hours_{MOCij}\right) \tag{10}$$

$$\begin{aligned} E_{FOLj} = C \times (&\sum_{i=1}\left(Emission_{FOLij} \times Consumption_{FOLij} \times Hours_{FOLij}\right) \\ &+ \sum_{i=14}(Emission_{FOi} ETotalFOL \\ &= E_{TotalFOL(42T)} + E_{TotalFOL(25T)} + E_{TotalFOL(25THELI)} + E_{TotalFOL(16T)} \\ &+ E_{TotalFOL(5T)} + E_{TotalFOL(3T)} \end{aligned} \tag{11}$$

$$E_{HWTj} = C \times \sum_{i=1}^{15}\left(Emission_{HWTij} \times Consumption_{HWTij} \times Hours_{HWTij}\right) \tag{12}$$

Total emissions for all categories of equipment can be expressed as:

$$E_{TOTAL} = \sum_{i=1}^{M} E_{TOTALi} \tag{13}$$

$$E_{TOTAL} = C \times \sum k \sum_{i=1}^{n}\left(Hours_{ij} \times Consumption_{ij} \times Emission_{ij}\right) \tag{14}$$

WHERE;

The constant factor C (0.001) is used to ensure the proper units are maintained in the calculations.

E_{TOTAL} represents the total emissions produced by all equipment types combined.

$Hours_{ij}$ is the number of hours each machine operates, $Consumption_{ij}$ is the consumption per hour, and $Emission_{ij}$ is the emission factor for each pollutant.

Berthing Tugs (BRT), Pilot Boats (PLB), Mooring Boats (MOB), Patrol Boats (POB), Hydrograph Boat (HOB), Harbour Mobile Cranes (HOMC), Rubber-Tired Gantry Crane (RTG), Reach Stackers (RST), Tractors (TRC), Mobile Cranes (MOC), Forklifts (FOL), Highway Trucks (HWT).

3.1.1 Mamdani and Sugeno Fuzzy inference systems

In the Mamdani fuzzy system, a fuzzy set A is defined with five memberships corresponding to pollutants: CO (a), NOx (b), SO2 (c), PM10 (d), and POC (e). The membership functions characterize the degree of association of each pollutant with the fuzzy set, allowing for a nuanced representation of their impact on emission reduction targets.

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TABLE 1 Equipment and Emission factors Data from Equipment at Dar es Salaam Port (jan-december2022).

Equipment type		Amount	Code	Engine capacity	Sources of power	Conspution per hour (L)	Emission factor per pounds/1,000 L of fuel burned				
							CO	NO	SO2	PM10	POC
Berthing tugs		6	BRT (1 ….. 6)	5,000 HP 1,000 HP 10,000 HP 3,000 HP	Diesel engines	150 30 500 100 150 40	5.8	3.67	3.3	0.2	0.03
Pilot boats		4	PLB (1 …. 4)	1,000 HP	Diesel engines	80	2.2	2.1	1	0.12	0.02
Mooring boats		1	MOB (1)	2500HP	Diesel engines	230	5.2	3	3	0.18	0.02
Patrol boats		2	POB (1 … 2)	500HP 1000HP	Diesel engines	50 80	2	1.2	2.8	0.08	0.12
Hydrograph boat		1	HOB (1)	100HP	Diesel engines	38	2	8	1.2	0.08	0.12
Harbour mobile cranes		11	HOMC (1 … 11)	1,000 HP	Diesel engines	100	10.15	2.68	0.56	0.11	0.08
RTG		2	RTG (1 … 2)	1,000 HP	Diesel engines	100	3	1.5	0.5	0.1	0.1
R/STACKERS (45T)		26	RST (1 … 26)	300 HP	Diesel engines	50	2.5	1.2	0.4	0.1	0.1
Tractors		48	TRC (1 … 48)	100 HP 200HP	Diesel engines	25 45	0.99	0.51	0.2	0.11	0.11
Mobile cranes		9	MOC (1 … 3)	2000HP	Diesel engines	75 50	10	3	0.5	0.1	0.1
Forklifts	42T	3	FOL (42T) (1 .. 3)	300HP	Diesel engines	100 50	2.5	1.2	0.4	0.1	0.1
	25T	4	FOL (25T) (1 … 4)	100HP	Diesel engines	50	0.64	1.67	0.37	0.07	0.16
	25T HELI	4	FOL (25T_HELI (1 .. 4)	100HP	Diesel engines	20	0.64	1.67	0.37	0.07	0.16
	16T	18	FOL (16T) (1 .. 18)	50HP	Diesel engines	20	0.106	1.2	0.17	0.2	0.2
	5T	50	FOL (5T) (1 .. 50)	35HP	Diesel engines	15	0.18	1.27	0.35	0.8	0.9
	3T	44	FOL (3T) (1 .. 44)	35HP	Diesel engines	15	0.18	1.27	0.35	0.8	0.9
Highway trucks		15	HWT (1 .. 15)	600HP	Diesel engines	15	4	3	0.3	0.1	0.1
Buses		9	BSS (1 .. 9)	380HP	Diesel engines	13	4	3	0.3	0.1	0.1
Lorries		20	LOR (1 … 20)	600HP	Diesel engines	15	4	3	0.3	0.1	0.1

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TABLE 1 (*Continued*) Equipment and Emission factors Data from Equipment at Dar es Salaam Port (jan-december2022).

Equipment type	Amount	Code	Engine capacity	Sources of power	Conspution per hour (L)	Emission factor per pounds/1,000 L of fuel burned				
						CO	NO	SO2	PM10	POC
Fire tenders	5	FIT (1 . . . 5)	380HP	Diesel engines	13	4	3	0.3	0.1	0.1
Portal cranes	8	POC (1 .. 8)	2000HP	Diesel engines	75	10	3	0.5	0.1	0.1

Total working hours per type equipments (jan- December, 2022)											
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2380	2348	1956	2163	2636	2423	2968	2622	2490	1617	1660	2325
1086	888	1319	903	908	1603	1103	1823	1585	1165	1761	901
10	441	451	348	582	691	592	326	159	209	548	643
215	912	997	915	756	653	686	54	611	495	742	661
50	527	245	103	169	517	602	270	495	391	292	278
4582	4697	6047	3853	3331	4241	4449	3664	4532	3869	3274	4285
721	1126	1009	769	1212	687	36	1225	756	705	694	1050
9457	9387	9342	9440	8998	8590	9069	8495	9270	9695	8577	8555
17811	18857	18343	15042	15858	18214	17576	17166	15336	16705	15789	17679
3835	3136	3102	3663	3506	4400	3442	3468	4388	3952	3851	1800
44214	46813	45351	43307	46567	45152	43686	46268	45533	43960	44153	46736
7939	5555	7382	6992	7262	6593	4574	6337	8937	6423	5632	6919
2850	3906	3193	3076	3540	3313	4182	3221	3945	3995	3070	4221
7313	6419	5737	7536	6346	6722	7331	6648	6638	7352	7915	7182
189	226	182	226	224	124	180	224	204	205	193	208
3374	2686	3547	2432	2513	2997	3399	2922	2524	2041	2472	2908

CO, Carbon Monoxide (CO), which consists of one carbon atom and oxygen atom.
NO, Nitrogen Oxides (NO), the subscript here indicates the variable number of nitrogen and oxygen atoms in these molecules.
SO_2, Sulfur Dioxide (SO_2), which consists of one sulfur atom and two oxygen atoms.
PM_{10}, Particulate Matter (PM_{10}), indicating particles with a diameter of 10 μm or less.
POC, Particulate Organic Carbon (POC), which represents the organic carbon fraction of particulate matter.

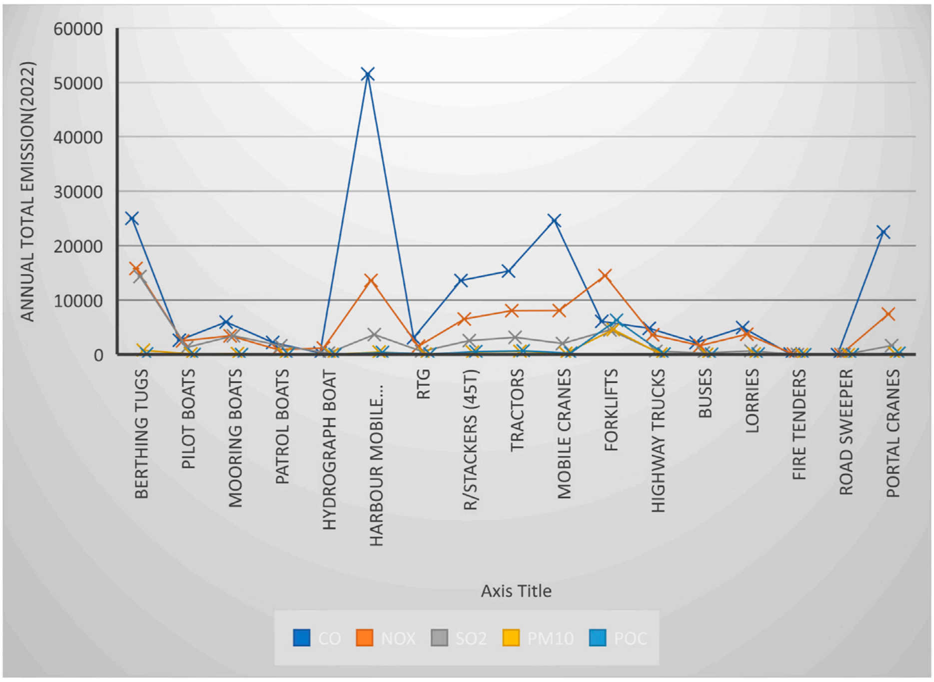

FIGURE 2
Annual emission from port equipment (2022).

The Sugeno fuzzy model operates similarly, employing fuzzy sets for CO, NOx, SO2, PM10, and POC. However, the membership functions (a, b, c, d, e) are determined based on a different fuzzy logic approach. The Sugeno model is known for its ability to provide more precise and specific control actions, making it suitable for situations where a clear, quantitative output is desired.

These fuzzy sets and membership functions form the foundation of the Mamdani and Sugeno fuzzy inference systems used in the emission reduction analysis. They enable the models to interpret complex and uncertain relationships between input variables (emission levels) and output variables (emission reduction targets) for each equipment type in Dar es Salaam Port.

The following expressions from 1 to 14 are derived for total emission calculation.

Define a fuzzy set A of five membership, A = {Co., No_x, So_2, PM_{10}, POC}

Member ship function.

1. CO, denoted as a
2. No_x, denoted as b
3. So_2, denoted as c
4. PM_{10}, denoted as d
5. POC, denoted as e

$$A = \{x, CoA(x), NoxA(x), SoA(x), PM_{10}A(x), PcoA(x)\} \quad (15)$$

$$\begin{cases} a > 1000, (a - (a^*50\%)) \\ b > 1000, (b - (b^*50\%)) \\ c > 1000, (c - (c^*50\%)) \\ d > 1000, (d - (d^*50\%)) \\ e > 1000, (e - (e^*50\%)) \end{cases} \quad (16)$$

$$y = w_1(a - 0.5a) + w_2(b - 0.5b) + w_3(c - 0.5c) + w_4(d - 0.5d) + w_5(e - 0.5e) \quad (17)$$

Where: y is total emission optimization target (50%)

w is constant factor (0.001) is used to ensure the proper units are maintained in the calculations.

4 Results from emission analysis, mamdani and sugeno fuzzy and strategic roadmap for facilities emission reduction in Dar Es Salaam Port

4.1 Results from comprehensive analysis

RTGs display a well-balanced emission profile, making moderate contributions to CO, NOx, and other pollutants. Their pivotal role in container handling positions them as a key focus for emissions reduction efforts. Exploring advanced technologies or cleaner energy sources specific to RTGs is pivotal for fostering sustainable port operations. In 2022, RTGs collectively discharged approximately 3093 pounds of CO, 1546.5 pounds of NOx, 586 pounds of SO2, 83.48054 pounds of PM10, and 103.1 pounds of POC as shown in Table 2.

The significant emissions from Reach Stackers, especially in CO and NOx, underscore the need for tailored strategies. As these machines are extensively used in container stacking, optimizing their efficiency and exploring cleaner fuel alternatives are imperative for mitigating their environmental impact. In 2022, Reach Stackers collectively emitted approximately 13609.375 pounds of CO, 6532.5 pounds of NOx, 2565.3 pounds of SO2, 456.68919 pounds of PM10, and 544.375 pounds of POC as shown in Figure 3.

The extensive fleet of tractors poses both challenges and opportunities. While their emissions are noteworthy, they also present a wide scope for impactful interventions. Exploring electric or hybrid alternatives and optimizing operational schedules could significantly diminish their overall emissions. In 2022, tractors collectively emitted approximately 15338.826 pounds of CO, 8076.714 pounds of NOx, 3172.7538 pounds of SO2, 595.71712 pounds of PM10, and 702.314 pounds of POC.

Mobile Cranes, with their diverse engine capacities, exhibit varied emission levels. Identifying emission hotspots among different crane types is crucial for targeted improvements. The transition to cleaner technologies or retrofitting existing cranes with emission control systems could enhance their overall sustainability. In 2022, mobile cranes collectively emitted approximately 24593.85 pounds of CO, 8108.255 pounds of NOx, 2043.705 pounds of SO2, 224.80873 pounds of PM10, and 275.1425 pounds of POC.

Forklifts, spanning different tonnages, significantly contribute to emissions. Given their widespread use, implementing a systematic replacement strategy with electric forklifts or retrofitting existing ones with emission control devices could yield substantial reductions. In 2022, forklifts collectively emitted approximately 6104.8854 pounds of CO, 14488.749 pounds of NOx, 4535.2686 pounds of SO2, 4623.6128 pounds of PM10, and 6320.955 pounds of POC.

Highway Trucks emerge as key contributors to emissions, reflecting their crucial role in cargo transportation. Strategies to enhance fuel efficiency, explore alternative fuels, and optimize routes can significantly reduce emissions in this segment. In 2022, highway trucks collectively emitted approximately 4832.1 pounds of CO, 3624.075 pounds of NOx, 622.539 pounds of SO2, 98.754448 pounds of PM10, and 120.8025 pounds of POC.

Buses, with their frequent intra-port transport role, exhibit moderate emissions. Considering their role in employee transportation, exploring cleaner fuel options or transitioning to electric buses could align with sustainability objectives. In 2022, buses collectively emitted approximately 2210.624 pounds of CO, 1657.968 pounds of NOx, 306.0213 pounds of SO2, 46.353956 pounds of PM10, and 55.2656 pounds of POC.

The emissions from lorries underscore their significance in the port's logistics chain. Implementing logistics optimization strategies, exploring alternative fuels, and enhancing vehicle maintenance practices can contribute to emissions reduction. In 2022, lorries collectively emitted approximately 4988.34 pounds of CO, 3741.255 pounds of NOx, 671.8815 pounds of SO2, 105.60361 pounds of PM10, and 124.7085 pounds of POC.

While fire tenders have a relatively low overall contribution to emissions, exploring cleaner technologies or alternative fuels can enhance their environmental performance. In 2022, fire tenders collectively emitted approximately 121.472 pounds of CO, 91.104 pounds of NOx, 13.7085 pounds of SO2, 2.5070432 pounds of PM10, and 3.0368 pounds of POC.

Portal Cranes, with their substantial emissions, necessitate targeted strategies. Given their pivotal role in cargo handling, adopting advanced technologies or transitioning to cleaner energy sources can significantly reduce their environmental impact. In 2022, portal cranes collectively emitted approximately 22515.6 pounds of CO, 7466.28 pounds of NOx, 1644.5625 pounds of SO2, 214.65012 pounds of PM10, and 253.62 pounds of POC.

The collective analysis of emissions from diverse port equipment types reveals a complex but actionable landscape. Each category, from RTGs to lorries, contributes to the intricate tapestry of emissions within the port environment. Understanding these nuances is critical for formulating effective strategies that address the specific challenges posed by each equipment type.

In 2022, the total emissions from all equipment types amounted to 185,163 pounds of CO, 92,908.4 pounds of NOx, 40,842.4 pounds of SO2, 8,067.53 pounds of PM10, and 9,178.614 pounds of POC. This comprehensive view not only quantifies the environmental impact but also provides a benchmark for evaluating the success of future sustainability initiatives.

The findings underscore the importance of targeted interventions. For RTGs, which exhibit a balanced emission profile, exploring advanced technologies tailored to their unique functions could significantly reduce their environmental footprint. Reach Stackers, with substantial emissions, demand strategies that optimize efficiency and explore cleaner fuel alternatives.

The extensive fleet of tractors presents both challenges and opportunities. While their emissions are notable, they also provide a broad canvas for impactful interventions. The significant emissions from mobile cranes, with their varied engine capacities, showcase diverse emission levels. Identifying emission hotspots among different crane types can inform targeted improvements.

Forklifts, spanning different tonnages, collectively contribute significantly to emissions. Implementing a systematic replacement strategy with electric forklifts or retrofitting existing ones with emission control devices could yield substantial emissions reductions. Highway trucks, as key contributors to emissions, reflect their crucial role in cargo transportation. Strategies to enhance fuel efficiency, explore alternative fuels, and optimize routes can contribute to substantial emissions reduction in this segment.

Buses, lorries, and fire tenders, each with its role in intra-port transport, showcase varying levels of emissions. Strategies for transitioning to cleaner fuel options or electric alternatives align with sustainability objectives.

4.2 Results from Mamdani fuzzy system for emission reductions for each specific equipment

In this section, we present the outcomes derived from employing the Mamdani Fuzzy System to reduce emissions from various equipment types. By examining the specific strategies developed for individual equipment categories, we aim to illustrate the effectiveness of fuzzy logic-based approaches in achieving emission reduction goals. Through this analysis, we provide insights into the tailored solutions generated by the Mamdani Fuzzy System, shedding light on its role in enhancing

TABLE 2 Results from comprehensive analysis.

Equipment	Annual total emission (jan-dec 2022) in pound				
Type	CO	NOx	SO2	PM10	POC
Berthing tugs	25009	15824	14349	777	129
Pilot boats	2648	2528	1306	124	24
Mooring boats	5980	3450	3450	187	23
Patrol boats	2231	937	1626	41	71
Hydrograph boat	299	1197	281	10	18
Harbour mobile cranes	51586	13621	3666	474	407
Rtg	3093	1547	586	83	103
R/stackers (45t)	13609	6533	2565	457	544
Tractors	15339	8077	3173	596	702
Mobile cranes	24594	8108	2044	225	275
Forklifts	6105	14489	4535	4624	6321
Highway trucks	4832	3624	623	99	121
Buses	2211	1658	306	46	55
Lorries	4988	3741	672	106	125
Fire tenders	121	91	14	3	3
Road sweeper	2	18	3	2	3
Portal cranes	22516	7466	1645	215	254
Emission total	185163	92908	40842	8068	9179

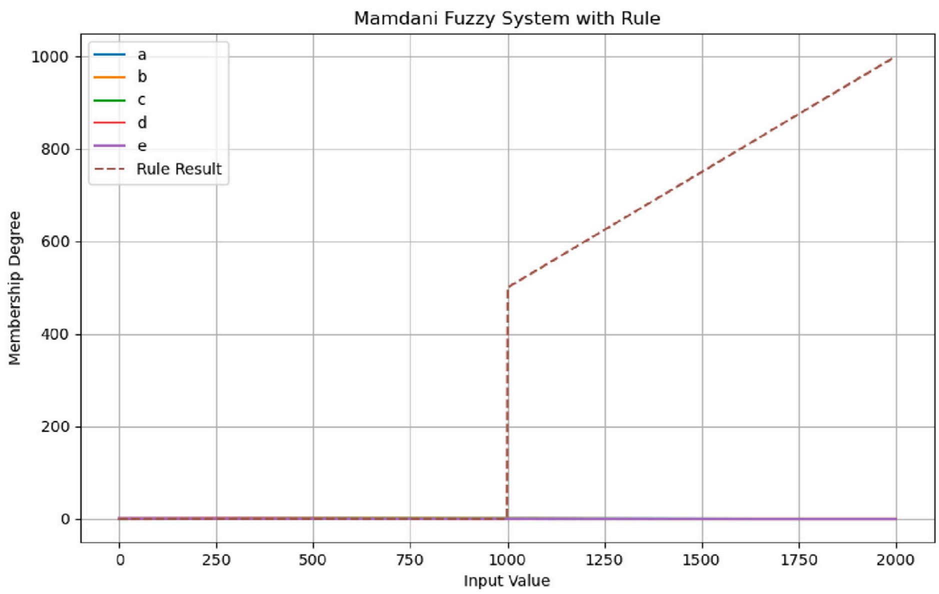

FIGURE 3
Fuzzy system with rule.

TABLE 3 Emission reductions for each specific equipment.

Equipment	Emission reduction Terget for each equipment				
Type	CO	NOx	SO2	PM10	POC
Berthing tugs	12504	7912	7174	776	129
Pilot boats	1323	1263	653	124	24
Mooring boats	2990	1725	1725	18	23
Patrol boats	1115	936	813	40	71
Hydrograph boat	299	598	280	9	17
Harbour mobile cranes	25793	6810	1833	474	406
RTG	1546	773	586	83	103
R/STACKERS (45T)	6804	3266	1282	456	544
Tractors	7669	4038	1586	595	702
Mobile cranes	12296	4054	1021	224	275
Forklifts	3052	7244	2267	2311	3160
Highway trucks	2416	1812	622	98	120
Buses	1105	828	306	46	55
Lorries	2494	1870	671	105	124
Fire tenders	121	91	13	2	3
Road sweeper	1	17	2	2	2
Portal cranes	11257	3733	822	214	253
Total	92793	46977	21663	5755	6018

environmental sustainability across diverse equipment applications as shown in Table 3.

4.3 Results from Sugeno fuzzy system for emission reductions for each specific equipment

By examining the outcomes specific to each equipment type, we aim to elucidate the effectiveness of Sugeno fuzzy logic-based approaches in achieving targeted emission reduction goals. Through this analysis, we provide insights into the tailored strategies developed by the Sugeno Fuzzy System for enhancing environmental sustainability within distinct equipment applications as shown in Table 4.

The Mamdani and Sugeno fuzzy systems were applied comprehensively to assess and target emission reductions across various equipment types in Dar es Salaam Port as shown in Figure 4. In the Mamdani model, Berthing Tugs were earmarked for substantial reductions in CO, NOx, and SO2 emissions, emphasizing PM10 and POC.

Pilot Boats focused on CO, NOx, and PM10, with specific targets for SO2 and POC, while Mooring Boats prioritized CO and NOx, equally addressing SO2 and PM10. Patrol Boats sought significant reductions in CO, NOx, and SO2, with emphasis on PM10 and POC. Hydrograph Boat aimed at reducing CO and NOx, with attention to SO2, PM10, and POC.

Harbour Mobile Cranes targeted reductions in all pollutants, particularly CO and NOx, with substantial goals for PM10 and POC. RTG aimed at reducing CO and NOx, emphasizing PM10 and POC. Reach Stackers prioritized CO, NOx, and PM10, with specific goals for SO2 and POC. Tractors emphasized CO, NOx, and POC, with specific targets for SO2 and PM10. Mobile Cranes sought substantial reductions across all pollutants, focusing on CO and NOx, with specific targets for PM10 and POC.

Forklifts had significant targets for reducing NOx, SO2, PM10, and POC, emphasizing CO. Highway Trucks targeted reductions in CO and NOx, with specific goals for SO2 and POC. Buses emphasized CO, NOx, and PM10, with specific targets for SO2 and POC. Lorries had significant targets for reducing CO, NOx, and POC, with emphasis on SO2 and PM10. Fire Tenders targeted reductions in CO, NOx, and PM10, with specific goals for SO2 and POC. Road Sweeper focused on reducing NOx and PM10, with minimal targets for CO, SO2, and POC. Portal Cranes aimed at reductions across all pollutants, particularly CO and NOx, with substantial goals for PM10 and POC.

In the Sugeno model, similar patterns were observed across equipment types, with specific numerical targets varying, indicating the adaptability and effectiveness of both fuzzy systems in formulating precise strategies for emission reductions as shown in. The cumulative targets for both models encompassed a holistic approach, addressing CO, NOx, SO2, PM10, and POC emissions throughout the port. These results provide a nuanced

TABLE 4 Emission reductions for each specific equipment.

Equipment	Emission reduction terget for each equipment				
Type	CO	NOx	SO2	PM10	POC
Berthing tugs	3751	2374	2152	777	129
Pilot boats	397	379	196	124	24
Mooring boats	897	518	518	187	23
Patrol boats	335	937	244	41	71
Hydrograph boat	299	180	281	10	18
Harbour mobile cranes	7738	2043	550	474	407
RTG	464	232	586	83	103
R/STACKERS (45T)	2041	980	385	457	544
Tractors	2301	1212	476	596	702
Mobile cranes	3689	1216	307	225	275
Forklifts	916	2173	680	694	948
Highway trucks	725	544	623	99	121
Buses	332	249	306	46	55
Lorries	748	561	672	106	125
Fire tenders	121	91	14	3	3
Road sweeper	2	18	3	2	3
Portal cranes	3377	1120	247	215	254
Total	28133	14825	8237	4138	3806

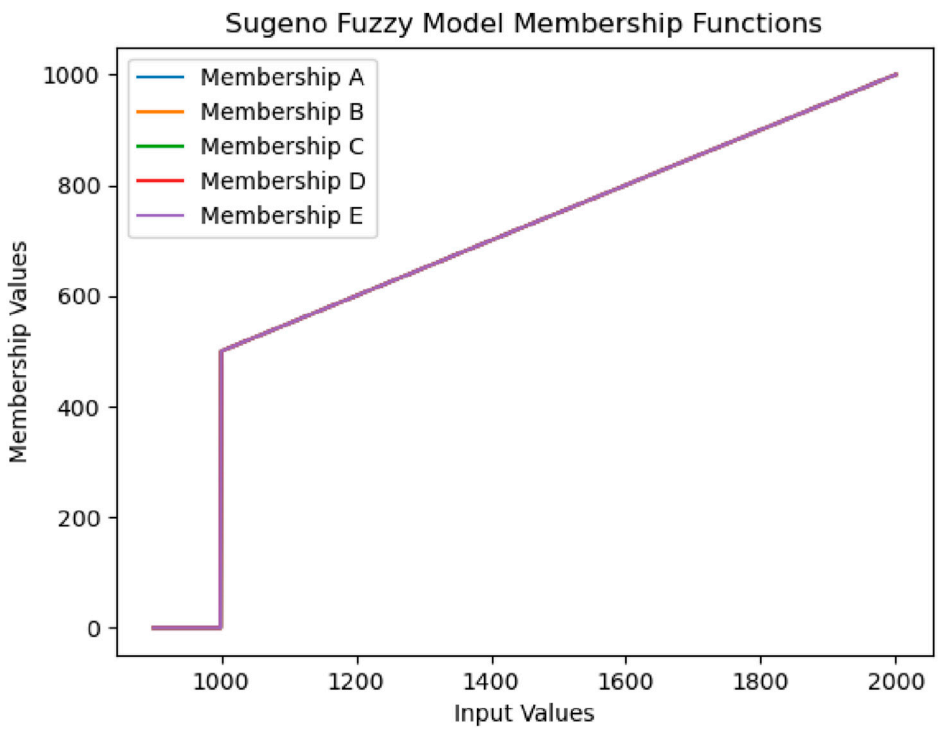

FIGURE 4
Sugeno fuzzy model membership functions.

TABLE 5 Strategic Roadmap for facilities Emission Reduction in Dar es Salaam Port.

Equipment Type	Findings	Optimization strategies
Berthing Tugs	Berthing Tugs show a significant contribution to CO, NOx, and other pollutants	Advanced Engine Technologies: Explore advanced engine technologies for berthing tugs to reduce emissions Fuel Efficiency Measures: Implement fuel efficiency measures to optimize their environmental impact
Pilot Boats	Pilot Boats exhibit moderate emissions, especially in CO and NOx	Fuel Transition: Consider transitioning to cleaner fuel options for pilot boats Regular Maintenance: Ensure regular maintenance to keep engines running efficiently
Mooring Boats	Moorings Boats contribute notably to SO2 emissions	SO2 Reduction Technologies: Explore technologies that can specifically reduce SO2 emissions from mooring boats Alternative Fuels: Investigate the feasibility of using alternative fuels for reduced environmental impact
Patrol Boats	Patrol Boats, with varying engine capacities, contribute to CO, NOx, and other pollutants	Engine Upgrade: Consider upgrading patrol boat engines to more fuel-efficient and cleaner options Operational Optimization: Optimize patrol boat operations to minimize emissions
RTGs (Rubber-Tired Gantry Cranes)	RTGs contribute moderately to CO, NOx, and other pollutants due to their role in container handling	Advanced Technologies: Investigate advanced technologies like hybrid systems or electrification for RTGs to reduce reliance on traditional diesel engines Operational Optimization: Implement strategies to optimize RTG operations, including efficient container handling and reduced idle times
Reach Stackers	Reach Stackers contribute substantially to CO and NOx emissions	Efficiency Optimization: Optimize the efficiency of Reach Stackers in container stacking operations, reducing the time and energy required Cleaner Fuel Alternatives: Explore the feasibility of using cleaner fuel alternatives, such as biodiesel or compressed natural gas (CNG), to reduce emissions
Tractors	Tractors have notable emissions, presenting both challenges and opportunities	Electric or Hybrid Alternatives: Investigate the adoption of electric or hybrid tractors to reduce emissions significantly Operational Optimization: Optimize the scheduling and routing of tractors to minimize their emissions while maintaining efficient port operations
Mobile Cranes	Mobile Cranes exhibit diverse emission levels based on engine capacities	Emission Hotspot Identification: Identify emission hotspots among different types of mobile cranes and focus on targeted improvements Transition to Cleaner Technologies: Explore the transition to cleaner technologies, such as electric or hybrid systems, for mobile cranes
Forklifts	Forklifts, spanning different tonnages, collectively contribute significantly to emissions	Systematic Replacement: Implement a systematic replacement strategy, gradually phasing out traditional forklifts in favor of electric ones Retrofitting: Retrofit existing forklifts with emission control devices to improve their environmental performance
Highway Trucks	Highway Trucks play a crucial role in cargo transportation, contributing to emissions	Fuel Efficiency Enhancements: Implement strategies to enhance fuel efficiency in highway trucks, such as regular maintenance and optimized driving practices Exploration of Alternative Fuels: Explore the feasibility of using alternative fuels like liquefied natural gas (LNG) or hydrogen for highway trucks
Buses	Buses showcase moderate emissions due to their role in intra-port transport	Cleaner Fuel Options: Explore cleaner fuel options for buses, such as biodiesel or compressed natural gas (CNG) Transition to Electric Buses: Consider transitioning to electric buses for intra-port transport to align with sustainability objectives
Lorries	Lorries have a significant impact on emissions in the logistics chain	Logistics Optimization: Implement logistics optimization strategies to streamline the movement of lorries within the port, reducing unnecessary idling and emissions Alternative Fuels: Explore alternative fuels for lorries, such as biodiesel or hydrogen, to contribute to emissions reduction
Fire Tenders	Fire tenders have a relatively low overall contribution to emissions	Cleaner Technologies: Explore cleaner technologies for fire tenders, such as electric or hybrid systems Alternative Fuels: Consider using alternative fuels, like biodiesel, for fire tenders
Portal Cranes		

(Continued on following page)

TABLE 5 (*Continued*) Strategic Roadmap for facilities Emission Reduction in Dar es Salaam Port.

Equipment Type	Findings	Optimization strategies
	Portal Cranes have substantial emissions due to their pivotal role in cargo handling	Advanced Technologies: Adopt advanced technologies such as regenerative braking or electrification for portal cranes to reduce emissions Emission Reduction Measures: Implement specific measures during cargo handling to minimize emissions, such as optimizing lifting operations and using cleaner fuels
Forklifts	Forklifts collectively contribute significantly to emissions	Systematic Replacement: Implement a systematic replacement strategy with electric forklifts for substantial emissions reductions Retrofitting: Retrofit existing forklifts with emission control devices for improved environmental performance

TABLE 6 RMSE results for emission analysis.

Pollutant	RMSE
CO	8546.523930471245
NOx	3692.943342296462
SO2	2028.2687778729223
PM10	562.4808493472049
POC	766.6553409223117

and tailored roadmap for the strategic reduction of emissions in Dar es Salaam Port as depicted in Table 5, showcasing the versatility of fuzzy inference systems in addressing complex environmental challenges.

4.4 Root mean square error (RMSE) results for emission analysis

The RMSE values calculated for each pollutant indicate the average deviation of the actual emissions from the target emissions. RMSE is a measure of the accuracy of the emission reduction targets:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(A_i - T_i)^2}$$

where: N is the number of observations (equipment types).

- Ai is the actual emission value for the *i*th observation.
- Ti is the target emission value for the *i*th observation.

$$\text{Reduction\%} = \left(\frac{TAE - TTE}{TAE}\right) \times 100$$

Where: TAE is Total Actual Emissions.

TTETotal Target Emissions.

The significant reduction in emissions, particularly for CO (49.89%), NOx (49.45%), and SO2 (46.98%), indicates effective emission reduction measures. These substantial improvements reflect successful efforts in curbing these pollutants. However, the RMSE values reveal deviations from the targets, suggesting the need for further refinement in emission control strategies to achieve more accurate reductions.

For example, the high RMSE value for CO (8546.52) suggests that while the emission reduction efforts have been effective, there is a considerable deviation from the target emissions. Similarly, the RMSE for NOx (3692.94) and SO2 (2028.27) indicate that, despite significant reduction percentages, there is still room for optimization to align actual emissions more closely with targets.

The RMSE for PM10 (562.48) and POC (766.66) are comparatively lower, yet they still highlight areas where precision can be improved. The reduction percentages for PM10 (30.88%) and POC (34.51%) show meaningful progress, but the corresponding RMSE values indicate that achieving closer alignment with targets is necessary for further improvement.

The analysis demonstrates substantial improvements in emission reduction, but the RMSE values provide insights into the precision of these efforts, highlighting the potential for further optimization in emission control strategies.

4.5 Strategic Roadmap for facilities Emission Reduction in Dar es Salaam Port

5 Discussion

The discussion section provides a comprehensive analysis of the emissions across various equipment types within the port environment, highlighting the significance of targeted interventions to reduce environmental impact. Each equipment category presents unique challenges and opportunities, necessitating tailored strategies for emissions reduction. By quantifying emissions and identifying key contributors, this discussion sets the stage for informed decision-making and effective implementation of sustainability initiatives within the port.

The Mamdani and Sugeno fuzzy systems were applied comprehensively to assess and target emission reductions across various equipment types in Dar es Salaam Port. As shown in Table 4 and Figure 4, specific numerical targets were developed for each equipment type, indicating the adaptability and effectiveness of both fuzzy systems in formulating precise strategies for emission reductions. The Mamdani model emphasized reductions in CO, NOx, and SO2 emissions for Berthing Tugs, while Pilot Boats focused on CO, NOx, and PM10. Mooring Boats prioritized CO and NOx, and Patrol Boats sought significant reductions in CO, NOx, and SO2, emphasizing PM10 and POC. Harbour Mobile Cranes targeted reductions in all pollutants, particularly CO and

TABLE 7 Total emission reduction percentages.

Pollutant	Reduction percentage
CO	49
NOx	49
SO2	46
PM10	30
POC	34

NOx, with substantial goals for PM10 and POC. Similarly, the Sugeno model presented specific numerical targets, showcasing the versatility of fuzzy inference systems in addressing complex environmental challenges.

The results from the Sugeno fuzzy system for emission reductions are detailed in Table 4. For instance, Berthing Tugs were targeted to reduce CO emissions by 3,751 pounds and NOx emissions by 2,374 pounds. Harbour Mobile Cranes aimed for a reduction of 7,738 pounds of CO and 2,043 pounds of NOx. The total cumulative targets for both models encompassed a holistic approach, addressing CO, NOx, SO2, PM10, and POC emissions throughout the port. These results provide a nuanced and tailored roadmap for the strategic reduction of emissions in Dar es Salaam Port, demonstrating the combined strength of Mamdani and Sugeno FIS in enhancing environmental sustainability within distinct equipment applications.

The RMSE values calculated for each pollutant indicate the average deviation of the actual emissions from the target emissions, providing a measure of the accuracy of the emission reduction targets. As shown in Table 6, the RMSE for CO was 8,546.52, indicating a considerable deviation from the target emissions. The RMSE for NOx and SO2 were 3,692.94 and 2,028.27, respectively, suggesting the need for further refinement in emission control strategies to achieve more accurate reductions. However, the RMSE values for PM10 (562.48) and POC (766.66) were comparatively lower, highlighting areas where precision can be improved.

The significant reduction in emissions, particularly for CO (49.89%), NOx (49.45%), and SO2 (46.98%), reflects successful efforts in curbing these pollutants, as shown in Table 7. These substantial improvements underscore the effectiveness of the emission reduction measures implemented. The reduction percentages for PM10 (30.88%) and POC (34.51%) show meaningful progress, but the corresponding RMSE values indicate that achieving closer alignment with targets is necessary for further improvement.

The meticulous examination of emissions across various port equipment types reveals a complex yet actionable scenario. Each category, ranging from RTGs to lorries, contributes distinctively to the intricate fabric of emissions within the port environment. Grasping these nuances is imperative for devising effective strategies tailored to the unique challenges posed by each equipment type.

In 2022, the cumulative emissions from all equipment types totaled 185,163 pounds of CO, 92,908.4 pounds of NOx, 40,842.4 pounds of SO2, 8,067.53 pounds of PM10, and 9,178.614 pounds of POC. This comprehensive perspective not only quantifies the environmental impact but also establishes a benchmark for evaluating the success of forthcoming sustainability initiatives.

The results underscore the significance of targeted interventions. For RTGs, which exhibit a balanced emission profile, exploring advanced technologies specifically tailored to their unique functions could significantly reduce their environmental footprint. Reach Stackers, with substantial emissions, necessitate strategies that optimize efficiency and explore cleaner fuel alternatives. The extensive fleet of tractors presents both challenges and opportunities. While their emissions are noteworthy, they also provide a broad canvas for impactful interventions. The substantial emissions from mobile cranes, with their varied engine capacities, highlight diverse emission levels. Identifying emission hotspots among different crane types can inform targeted improvements. Forklifts, spanning different tonnages, collectively contribute significantly to emissions. Implementing a systematic replacement strategy with electric forklifts or retrofitting existing ones with emission control devices could yield substantial emissions reductions. Highway trucks, as key contributors to emissions, reflect their crucial role in cargo transportation. Strategies to enhance fuel efficiency, explore alternative fuels, and optimize routes can contribute to substantial emissions reduction in this segment. Buses, lorries, and fire tenders, each playing a role in intra-port transport, exhibit varying levels of emissions. Strategies for transitioning to cleaner fuel options or electric alternatives align with sustainability objectives.

This paper delves into specific overarching strategies, policies, and initiatives that port authorities can implement to coordinate emission reduction efforts across all equipment types. This may include regulatory frameworks, incentives for cleaner practices, and ongoing monitoring and assessment procedures. The outlined strategic roadmap for each equipment type, coupled with overarching initiatives, aims to guide Dar es Salaam Port toward a more sustainable and environmentally responsible future.

Comparatively, with (Elhamed and Mohamed, 2023), this paper on Dar es Salaam Port presents a comprehensive and detailed analysis of emissions, focusing on specific equipment types within the port. It provides tailored and nuanced recommendations for each category, emphasizing a strategic roadmap for emissions reduction. The findings are integrated to present a collective view of total emissions, underscoring the importance of targeted interventions for a greener and more sustainable port environment. while the other paper introduces the concept of green ports in a more general sense and applies it to the case of the Port of Damietta in Egypt. While it emphasizes the importance of addressing potential environmental threats, it lacks the specificity and detailed equipment-specific recommendations found in the Dar es Salaam Port paper. The emphasis in the latter is on the broader application of green port concepts, whereas the former delves deeply into the analytical depth of emissions from diverse equipment types.

6 Conclusion and recommendation

In this section, we delve into the discussion regarding the analysis of emissions across various equipment types within Dar es Salaam Port.

In the culmination of this thorough analysis, the examination of emissions across various equipment types within Dar es Salaam Port has revealed a complex yet actionable environmental scenario. Each category of equipment, ranging from Berthing Tugs to Portal Cranes, significantly contributes to the intricate tapestry of emissions within the port environment. These findings extend beyond mere quantification; they shed light on nuanced challenges and present unique opportunities for targeted interventions.

The aggregate emissions for the year 2022 amounted to 185,163 pounds of CO, 92,908.4 pounds of NOx, 40,842.4 pounds of SO2, 8,067.53 pounds of PM10, and 9,178.614 pounds of POC. These figures not only serve as quantitative indicators of the environmental burden but also as crucial benchmarks, emphasizing the need for strategic interventions to curb emissions throughout the port.

In light of the comprehensive analysis of emissions across diverse equipment types within Dar es Salaam Port, a set of strategic recommendations emerges to guide the port toward a sustainable and environmentally responsible future:

Equipment-Specific Strategies: Develop interventions tailored to the distinctive emission profiles of each equipment type. For instance, integrate advanced technologies for RTGs, optimize efficiency for Reach Stackers, and systematically replace traditional forklifts.

Regulatory Frameworks: Institute robust regulatory frameworks to enforce stringent emission reduction measures. This could involve establishing emission standards tailored to each equipment type and introducing incentives to encourage compliance.

Alternative Fuels: Actively explore and promote the adoption of alternative fuels, such as biodiesel, compressed natural gas (CNG), or hydrogen, to substantially reduce the overall carbon footprint resulting from port operations.

Technology Transition: Initiate investigations into transitioning to cleaner technologies, such as electric or hybrid systems, particularly for equipment types exhibiting elevated emission levels, such as Mobile Cranes and Portal Cranes.

Operational Optimization: Optimize the operational schedules and routes of equipment like Tractors and Lorries to minimize emissions without compromising port operations' efficiency.

Continuous Monitoring: Establish a continuous monitoring and assessment procedure to systematically track the efficacy of implemented measures. This approach ensures the identification of areas necessitating further enhancement.

Public Awareness: Roll out comprehensive public awareness campaigns to actively engage port stakeholders, including equipment operators, workers, and the local community, fostering a collective commitment to sustainable practices and emission reduction endeavors.

Generalization for Similar Applications: Extend the conclusions drawn from this study to inform and guide similar applications in other ports worldwide. The insights gained and strategies proposed can serve as valuable templates for addressing emissions reduction challenges in diverse port environments globally.

By implementing these recommendations, Dar es Salaam Port stands poised to embark on a trajectory marked by sustainability and environmental responsibility. Such measures not only serve to mitigate the port's environmental impact but also contribute to the growth of maritime activities in a responsible and resilient manner. The collaborative efforts of port authorities, operators, and the local community are indispensable in nurturing a port ecosystem that is economically vibrant and environmentally sustainable.

7 Future directions

1. Carbon Neutrality: In the pursuit of carbon neutrality, Dar es Salaam should intensify their efforts to reduce emissions from ship calls, cargo throughput, and transportation. This involves investing in cleaner technologies for ships, optimizing cargo handling processes to minimize emissions, and transitioning to electric or hybrid vehicles for inland transportation. Collaborations with environmental organizations and government incentives for green initiatives can further facilitate this transition.
2. Integrated Logistics: To enhance overall sustainability, the port can work towards integrating logistics operations. This entails creating seamless connections between various transportation modes, such as rail and water transport, to reduce reliance on carbon-intensive road transport. Embracing digital technologies like blockchain for supply chain transparency and efficiency can minimize delays and resource wastage, leading to a more sustainable and competitive port ecosystem.
3. Nature-Based Solutions: Recognizing the ecological importance of coastal areas, port can explore nature-based solutions. This includes initiatives like mangrove restoration to mitigate habitat destruction, absorb carbon dioxide, and bolster the resilience of the ports against climate change impacts like sea-level rise and extreme weather events. Collaboration with environmental NGOs and research institutions can provide valuable insights and resources for implementing such projects effectively.

These future directions align with global sustainability trends and can position of Dar es Salaam and as leader in green port initiatives, setting an example for sustainable maritime operations in the East African region.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

MK: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. HZ: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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